Part 2. Interstellar Medium

Section A. Invited Reviews

Mary Putman and Bart Wakker are enjoying a poster session.

New Views of the Magellanic Clouds
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New Magellanic Cloud Interstellar Matters

K.S. de Boer

Sternwarte, University of Bonn, D-53121 Bonn, Germany

Abstract.
Novel instrumentation has always led to new insights in the nature of the universe. Novel astronomical instrumentation is no exception. In numerous areas new instruments led to the detection of hitherto unknown phenomena. I will review some notable studies of the recent past with some emphasis on those dicoveries not extensively covered by others at this conference. Finally, very recent work based on ORFEUS echelle spectra is presented.

1. Introduction

New telescopes and new measuring techniques have always led to fast developments of knowledge and understanding in the particular research field. The research on the ISM of the Magellanic Clouds (MCs) is no different. The new satellites like ROSAT (X-ray maps), ISO (near and far IR photometry and spectroscopy), CGRO (Gamma rays), HST (imaging and spectroscopy in the visual and the UV), the space shuttle instruments HUT and ORFEUS (UV-photometry and spectroscopy), new ground based instruments like Hα interferometric mapping devices, IR-CCDs, the Australia Telescope (radiosynthesis), the NANTEN mm telescope (CO), and many others have shown what new windows the new techniques have opened. On many of these, presentations are made in this conference.

In this contribution I will review some notable studies from the bygone years. The choice is personal, thus biased, in part towards those pieces of research which otherwise might not be mentioned in this meeting. Before that I will review *what* we are actually looking at when we observe the interstellar medium in the Magellanic Clouds (and elsewhere). Finally, I will present the new results from ORFEUS echelle spectra of Magellanic Cloud stars.

2. WHAT is Actually Detected?

When we look at the Magellanic Clouds, the most conspicuous part of the ISM is formed by H II regions. We normally say we observe ionized gas, but what we see is, in fact, the *recombining* part of the ionised gas. This is gas in which T is low enough for recombination to really take place and in which the electron and proton density are large (relatively speaking). The optical (and also the radio) recombination lines therefore show us $\int n_e^2 \, dl$ of gas at $T \simeq 10^4$ K. Clearly, we preferentially see the densest parts (n_e^2) of the H II gas, thus essentially the *edges* of the H II regions.

The intensities of the forbidden optical and UV emission lines, like [O III], [N II], C III], etc., are based on collisional excitation. In principle one sees $\int n_e^2\, dl$ at the temperature where the particular ion can exist, but matters are complicated because of excitation saturation, so that in part one sees $\int n_{\rm ion} f_{\rm ul}\, dl$ (see Osterbrock 1988, p. 132 ff). Models of the emission spectrum from diffuse gas are available from Domgörgen & Mathis (1994).

In the radio continuum one sees the radiation produced by electrons moving through gas and scattered by the ions. Again the dense portions of the gas radiate best, we see thus n_e^2.

When we make H I 21 cm measurements, we detect $\int n_{\rm H}\, dl$ so H I 21 cm data give us basically $n_{\rm H}$. However, we need to know the length of the sight line, l, over which emission takes place. This is impossible in almost all situations.

The studies of CO (see also the nice maps obtained with NANTEN; this conference) show the existence of that molecule, a molecule easily destroyed by photons, therefore present only in gas shielded from photons. Moreover, the CO emission comes from an excited state. Thus we see basically the very dense and dusty neutral gas, $n_{\rm H}^2$.

Mochizuki et al. (1994) recently surveyed the LMC in the cooling line of [C II] at 158 μm. Their map shows us the gas able to populate the fine structure state of C II, an excitation which in dusty cool clouds is based on $n_{\rm C} \times n_e$ and thus $n_{\rm H} \times n_e$. On the surface of such clouds the excitation is rather based on the part of the radiation field with $\lambda \leq 1335$ Å being able to excite C II as well. So which of the two locations dominates the emission at the positions measured?

The X-ray maps (Einstein, ROSAT, ASCA) show the emission by very hot ($T \geq 10^6$ K) gas. Also here the emission is dominated by the densest parts of the gas, thus on n_e^2, at those high temperatures where the cooling is somewhat more efficient than at neigbouring. However, these X-rays are easily absorbed by neutral gas. The absence of X-rays may therefore mean either of two things: that there is no million degree gas at all or that there is an absorbing cloud in front of the X-ray emitting gas.

Finally, absorption lines measure just the column density $\int n_{\rm X} dl$, but always related to the temperature at which the given absorber can exist. Now we know the line of sight l, but the gas is surely not evenly spread. Another problem is the lack of background sources of radiation, both in the visual and the UV as well as in the radio domain. This then oftentimes is compounded by lack of sensitivity of the detector (or by our wish to observe fainter than possible!).

All these marvelous measurements lure us into combining them to derive nice and clean parameters for the gas. Alas, all these measurements are made with telescopes having different beam sizes for each type of measurement. Thus all the problems of beam-filling factors come into play. Furthermore, the spatial resolution is different, so that a position bright in two kinds of data need not mean it is the same gas making the two kinds of detected radiation.

In all these studies the distance information is meagre, in the sense that depth information is almost impossible to obtain.

In spite of all these limitations, very nice and important work has been carried out in past years.

3. Notable Studies Since 1990

A very compact paper giving important results from EUV spectroscopy is that by Clayton et al. (1996). With the HUT they observed stars in the LMC to study their UV extinction. They could show that the UV-extinction continues to rise from 1500 toward 950 Å as expected from IUE measurements. This is also in line with models for dust extinction (e.g. Aanestad 1989). Using WUPPE the UV-polarization was measured and was found to lie *above* the Serkowsi law. Although the spectra were only of modest spectral resolution, Clayton et al. (1996) could fit the broader spectral depressions with absorption in the Lyman and Werner H_2 absorption bands. Toward 2 stars they find $N(H_2)$ of 1-2 $\cdot 10^{20}$ cm^{-2}.

Of particular relevance for the physics of cool clouds are the 21 cm H I absorption line studies carried out by Mebold et al. (1991) in the Magellanic Stream and by Dickey et al. (1994) and Marx-Zimmer et al. (1999) in the LMC itself. In the Magellanic Stream no absorption was detected, indicating the Stream gas is warm. In the LMC a large number of cold absorption components has been discovered. The average temperature is as low as $T_c \simeq 30$ K, compared to about 60 K for galactic gas seen in 21 cm absorption (Marx-Zimmer et al. 1999).

The SMC has been completely mapped in Hα with the Marseille 2-D Fabry-Perot interferometer (le Coarer et al. 1993) providing us with velocity and intensity information. Also in the LMC various fields have been studied (see e.g. Rosado et al. 1996). Much more of this kind of work needs to be done in the LMC, in particular to get velocities for Hα to be related with the kinematics of shells and with the kinematics in the LMC on a large scale.

A further notable study deals with the comparison of all the wonderful measurements in the different emission lines in the 30 Dor region (Poglitsch et al. 1995). These emissions include those of Br γ, CO, [O I] 63 μm, [C II] 158 μm, H_2 in the near IR, along with the broad band IRAS fluxes. The observational problems of spatial coverage, spatial resolution, as well as of uncertainties in the depth structure become acutely visible in this study.

Depth structure can, however, be found using interstellar absorption lines. For that one needs a large number of stars, closely packed in the sky, and spread appropriately in distance. Such a study was carried out by Vladilo et al. (1993) in the field of SN 1987A in the LMC. Stars at the front side of a spatial structure show few absorption components, stars in the back all. The task is just the one of sequencing, since in reality the distances of the stars are only poorly known, in particular their relative distances at 50 kpc from us. In this way Vladilo et al. (1993) could derive some of the depth structure of the material in the field around SN 1987A.

Another possibility to find depth structure utilises the supernova light echos. SN 1987A was used for that by Spyromilio et al. (1995) and by Xu et al. (1995). Here the dust is mapped in 3 dimensions based on the time sequence of the clouds lighting up in the sky projected around SN 1987A. More details about the 3-D structure were derived from emission line spectra of the surrounding gas (Xu & Crotts 1999).

Time dependent *changes* in the ISM are seldom seen. The gas in the vicinity of SN 1987A showed such variations, which were analysed by Panagia et al. (1991).

The reality of an outer layer of gas at coronal temperatures around the LMC (de Boer & Savage 1980) is now confirmed. Wakker et al. (1998) used better data than available at that earlier epoch (see de Boer 1984) and demonstrated that abundant C IV absorption absolutely unrelated to the background stars is present indeed.

A large number of studies revolved around solving the nature of the supergiant shells in the LMC. In particular hot gas was demonstrated to exist inside LMC 4 (Bomans et al. 1994, 1996) and this structure did not originate in the collision with a high-velocity cloud (Domgörgen et al. 1995). Given the ages of the stars inside LMC 4 a large scale trigger for the star formation is required.

At the SE edge of the LMC Blondiau et al. (1996), using ROSAT data, detected X-ray emitting gas as well as shadowing of X-ray gas by dust clouds detected in IRAS maps. This is suggestive of a bow shock at the leading edge of the LMC and dense star forming gas in the interior. Including the LMC motion and the need to have a large scale star formation trigger for the making of the LMC supershells, the bow-shock induced star formation model was developed (de Boer et al. 1998a).

4. ORFEUS

Let me now turn to the new results from the ORFEUS experiment. The ORFEUS telescope for far-UV spectroscopy flew on the ASTRO-SPAS platform during two space shuttle missions. The ORFEUS telescope feeds the UCB intermediate dispersion spectrograph, working between 300 and 1400 Å with $\lambda/\Delta\lambda \simeq 3 \cdot 10^3$, and the Tübingen-Heidelberg echelle spectrograph, working between 900 and 1400 Å with $\lambda/\Delta\lambda \simeq 10^4$. The attached IMAPS produces high resolution spectra ($\lambda/\Delta\lambda \simeq 1.5 \cdot 10^5$) of bright (and thus galactic) stars (see Jenkins & Peimbert 1997). During the second mission of Nov.-Dec. 1996 the echelle spectrograph functioned well and five Magellanic Cloud stars have been measured (4 in the LMC, 1 in the SMC).

4.1. ORFEUS Echelle Spectra and H_2

The spectra, with a resolution of about 30 km s^{-1}, have been searched for the presence of absorption by H_2. The line of sight to one LMC star, LH 10:3120 (see de Boer et al. 1998b), and to the SMC star, HD 5980 (see Richter et al. 1998), both contain H_2 in quantities measurable in absorption in the Lyman and Werner bands. The molecule was found in all spectra at velocities pertaining to the Milky Way as well.

In the MC gas the population of the various J levels of H_2 does not follow a simple rule. As with galactic lines of sight, the lowest rotational levels are mainly populated through collisional excitation (thus showing $n_e \times n_{\rm H}$). The higher rotational levels are populated through the work of the radiation field. UV photons redistribute the level population to one related to the strength and shape of the radiation field convolved with the probabilities of the electronic transitions (Spitzer & Zweibel 1974).

LMC: Toward the star LH 10:3120, associated with N 11, the kinetic temperature derived from the lowest levels is $T \leq 50$ K (Richter et al. 1998a; de Boer et al. 1998b). Such a low temperature has not been seen in galactic H_2 gas (Spitzer et al. 1974). However, it seems to be in line with the very cold gas mentioned above as discovered in H I absorption studies (see Dickey et al. 1994, Marx-Zimmer et al. 1998). The total column density in front of LH 10:3120 is $N(H_2) \simeq 7 \cdot 10^{18}$ cm^{-2}.

SMC: Toward the star HD 5980, associated with NGC 346, two absorbing clouds are well resolved in the spectrum, *Cloud A* near +120 km s^{-1}, and *Cloud B* near 160 km s^{-1}. The kinematic temperature in *Cloud A*, which is seen in absorption only in levels $J \leq 2$, is $T \simeq 70$ K. In *Cloud B*, seen in levels $J \geq 5$, the UV pumping appears to be extremely strong leading to a level-population distribution equivalent to > 2350 K (Richter et al. 1998b), much higher than any found in the Milky Way (see Spitzer et al. 1974). Both clouds are seen in weak and blended absorption in levels $J = 3, 4$. The total column density in front of HD 5980 is $N(H_2) \simeq 5 \cdot 10^{16}$ cm^{-2}.

4.2. ORFEUS Echelle Spectra and O VI

O VI has been detected in absorption by gas in the halo of the Milky Way on the line of sight to the SMC star HD 5980 (Widmann et al. 1998). It also shows up at $v_{\rm rad} \simeq 140$ km s^{-1}, the 'normal' SMC velocity. Furthermore, it is detected at $v_{\rm rad} \simeq 300$ km s^{-1}, the velocity of exceptional gas noted before by de Boer & Savage (1980) and described in detail by Fitzpatrick & Savage (1983). Gas in this exceptional state (showing all species from Si II and C II through Si III to C IV, N V and O VI) most likely is produced by a supernova shock through gas in the foreground of HD 5980. This gas clearly deserves to be the subject of further investigation.

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References

Aanestad, P.A. 1989, ApJ, 338, 162

Blondiau, M.J., Kerp, J., Mebold, U., & Klein, U. 1997, A&A, 323, 585

Bomans, D.J., Dennerl, K., & Kürster, M. 1994, A&A, 283, L 21

Bomans, D.J., de Boer, K.S., Koornneef, J., & Grebel, E.K. 1996, A&A, 313, 101

Clayton, G.C., Green, J., Wolff, M.J., et al. 1996, ApJ, 460, 313

de Boer, K.S., & Savage, B.D. 1980, ApJ, 238, 86

de Boer, K.S., Braun, J.M., Vallenari, A., & Mebold, U. 1998a, A&A, 329, L 49

de Boer, K.S., Richter, P., Bomans, D.J., Heithausen, A., & Koornneef, J. 1998b, A&A, 338, L 5

Dickey, J.M., Mebold, U., Marx, M., Amy, S., Haynes, R.F., & Wilson, W. 1994, A&A, 289, 357

Domgörgen, H., & Mathis, J.S. 1994, ApJ, 428, 647

Domgörgen, H., Bomans, D.J., & de Boer, K.S. 1995, A&A, 296, 523

Fitzpatrick, E.L., & Savage, B.D. 1983, ApJ, 267, 93

Jenkins, E.B., & Peimbert, A. 1997, ApJ, 477, 265

le Coarer, E., Rosado, M., Georgelin, Y., Viale, A., & Goldes, G. 1993, A&A, 280, 365

Marx-Zimmer, M., Herbstmeier, U., Dickey, J.M., Stavely-Smith, L., Mebold, U., & Zimmer, F. 1999, A&A, to be subm.

Mebold, U., Greisen, E.W., Wilson, W., Haynes, R.F., Herbstmeier, U., & Kalberla, P.W.M. 1991, A&A, 251, L 1

Mochizuki, K., Nakagawa, T., Doi, Y., et al. 1994, ApJ, 430, L 37

Osterbrock, D.E. 1988, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*; Univ. Science Books, Mill Valley

Panagia, N., Gilmozzi, R., Macchetto, F., Adorf, H.-M., & Kirshner, R.P. 1991, ApJ, 380, L 23

Poglitsch, A., Krabbe, A., Madden, S., et al. 1995, ApJ, 454, 293

Richter, P., de Boer, K.S., Bomans, D.J., Heithausen, A., & Koornneef, J. 1998a, in: *The Magellanic Cloud and other dwarf galaxies*, (eds) T. Richtler & J.M. Braun, p. 189

Richter, P., Widmann, H., & de Boer, K.S., et al. 1998b, A&A, 338, L 9

Rosado, M., Laval, A., Le Coarer, E., Georgelin, Y.P., Amram, P., Marcelin, M., Goldes, G., & Gach, J.L. 1996, A&A, 308, 588

Spyromilio, J., Malin, D.F., Allen, D.A., Steer, C.J., & Couch, W.J. 1995, MNRAS, 274, 256

Spitzer, L., & Zweibel, E.G. 1974, ApJ, 191, L 127

Spitzer, L., Cochran, W.D., & Hirschfeld, A. 1974, ApJS, 28, 373

Vladilo, G., Molaro, P., Monai, S., et al. 1993, A&A, 274, 37

Wakker, B.P., Howk, J.C., Chu, Y.-H., Bomans, D., & Points, S.D., 1998, ApJ, 499, L 87

Widmann, H., de Boer, K.S., Richter, P., Kraemer, G., et al., 1998, A&A, 338, L 1

Xu, J., Crotts, A.P.S., & Kunkel, W.E., 1995, ApJ, 451, 806

Xu, J., & Crotts, A.P.S., 1999, ApJ, 511, 262

Discussion

Dennis Zaritsky: Are there many more lines of sight for which H_2 absorption could be detected with current instrumentation?

de Boer: In principle yes. There should be enough dense gas in front of the star to expect the molecules. But then the extinction should be small enough to not lose too much signal needed to record the spectrum. Whether ORFEUS will fly again is unclear. Hopefully FUSE, to be launched in 1999, will provide lots of opportunities.

Wolfgang Gieren: Can you estimate the depth of the LMC in the line of sight from the interstellar medium?

de Boer: Unfortunately not. What one can do, of course, is to find the sequence in depth of clouds and stars, but no, no depth in parsecs. However, taking the radial velocities of the gas clouds one can estimate how soon clouds might collide and by including probability estimates guess how many parsecs the separation in depth is.

Arlin Crotts: In response to the question regarding the lack of knowledge of the scale height of the gas in the LMC: the light echoes from SN 1987A show dust (and associated gas) spread over at least one kiloparsec in depth.

Daniel Wang: You did not mention any results from HST. Could you comment on the results, especially on absorption line studies?

de Boer: Several of those results will be presented by others. Yes, we detected CIV absorption to stars inside LMC 4 demonstrating the cavity is filled with hot gas (Bomans et al. 1996, A&A, 313, 101). And I am, of course, pleased that Wakker et al. (these proceedings) confirm (after 19 years of uncertainty; see de Boer 1984 in IAU Symp 108) the existence of coronal gas around the LMC.

Nolan Walborn: There is some current progress on interpreting the relative distribution of different emissions from 30 Doradus you showed, which will be presened by Monica Rubio this afternoon and myself tomorrow. The filaments west and northeast of R136 are interfaces between the outflows from the latter and dust clouds beyond, in which new star formation is being triggered. Hence, the filaments are bright in Brγ, while the CO and H_2 are concentrated beyond them, with respect to R136.